MNRAS 000, 1–10 (2024) Preprint 10 June 2024 Compiled using MNRAS LATEX style file v3.0

Are there Alien Technological Civilisations in the Milky Way?

10 June 2024

1 INTRODUCTION

One of the biggest unresolved questions facing humanity today is: are we alone? When making any attempt to answer such a broad question it is important to first clarify that the overwhelming lack of data precludes any meaningful numerical estimates regarding the abundance of alien civilisations. After all, the only life we know of is that which exists on the Earth – hardly a strong basis for statistical arguments. Yet, a more qualitative discussion of the factors at play in the development of a technological civilisation can prove fruitful, and may give an indication (even if unquantifiable) of their rarity.

This essay will discuss the likelihood of alien technological civilisations existing in the Milky Way. The focus will be on a broad definition of technological civilisation, more akin to ancient human civilisation rather than those which may have the capacity to communicate with us. There are many aspects to consider in such a discussion, ranging from planet habitability all the way to the development of intelligence in complex animals. We will start by considering the most basic tenets of life, how it is defined and what forms it can take, before moving on to an examination of planet habitability *and* stability. This will be followed by an exploration of how life develops from a non-living chemical basis to a highly intelligent, technologically-advanced species.

The aim of this essay will not be to impose a point of view on the reader (although my own opinion will be offered at the end) but rather to impartially weigh up as many considerations as possible and give the reader the freedom to draw their own conclusions.

2 CONSTRAINTS ON ALIEN LIFE

Any discussion about alien life requires some understanding of what form we expect life to take. After all, without knowing whether there are unending possibilities for different lifeforms in myriad environmental conditions or very narrow restrictions for extra-terrestrial life, we can't begin to discuss how likely it is to exist elsewhere.

This essay will use the definition of life provided in *Life in the Universe* (see footnotes) in which a living entity must be a self-organising bounded environment which maintains thermal disequilibrium with its surroundings by manipulating free energy and materials, and uses coded information and raw materials to reproduce its form in successive generations.

This section will break down the most basic components of life and what form those take on Earth, before moving on to consider how these might differ in alien life.

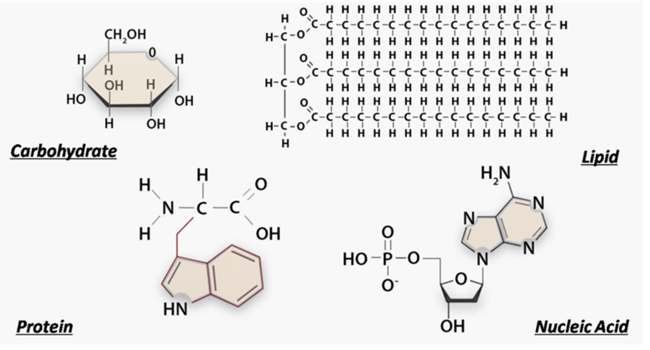

Figure 1. Some biologically important Carbon-based molecules. The complexity and variety that can be achieved with the four CHON elements is displayed. Reproduced from https://iteachly.com/macromolecules-biology-activity/.

2.1 The Building Blocks of Life

There are 4 fundamental components to all life on Earth:[1]

- Complex biochemicals.
- Water (a solvent).
- A means of storing information for extraction.
- Cellular structures.

The **complex biochemicals** used by all life on Earth (such as proteins, lipids and nucleic acids) are all built from a Carbon base. Carbon's ability to hold four stable yet modifiable atomic bonds at once allows it to form long molecular chains (macromolecules) that living organisms can manipulate to their advantage. A great chemical variety can be achieved from a limited selection of elements – mostly Hydrogen, Oxygen and Nitrogen (the so-called 'CHON' elements when combined with Carbon). See Figure 1 for some examples of the complexity that can be obtained from these four elements.

Life uses such chemicals in many different ways – carbohydrates serve as fuel and building materials, lipids are used to construct cell membranes and sub-cellular structures, and proteins (built from a selection of 20 amino acids) serve a variety of functions from catalysing chemical reactions to extracting and translating genetic information. Without such a varied chemical toolkit, life could not carry out the functions that facilitate its existence. Hence, a similarly diverse chemical basis would also be required for the existence of alien life.

The use of a chemical **solvent** is crucial to life as the dissolution of certain biologically important chemicals and the insolubility of some macromolecules allows structures and interfaces to exist, as well as the transport of chemicals through and within them.

[1] The discussion in this section is informed by *Biology* by Neil A. Campbell and Jane B. Reece, Seventh Edition (2005)

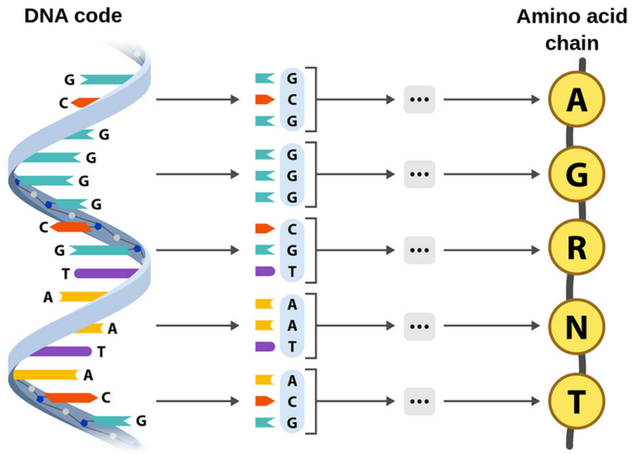

Figure 2. DNA molecules contain combinations of 4 different acids which are read in triplets to inform cells on which proteins to create. Reproduced from https://theory.labster.com/dna-code/.

Earth life uses water as its solvent. Water is an excellent life-sustaining medium due to its versatility as a solvent, its pH-stability and high specific heat capacity (by which it resists large pH and temperature fluctuations). Additionally, water possesses the rare property of being less dense as a solid than as a liquid. This means that when it freezes, it does so from the top-down rather than bottom-up. This is important for life on water-rich terrestrial surfaces because during periods of colder climates (an ice age for example) liquid water can be insulated beneath an icy surface, preserving the life that exists within it.
The **information storage** system used by life on Earth is made up of *nucleic acids*. These form DNA/RNA – the molecules that store genetic information and allow life to build complex biological structures and reproduce. Without some ability to carry out these functions, life simply could not exist.
Additionally, DNA uses a base-4 information system, meaning 4 bases can be combined in different combinations of 3 to produce 64 possible sequences. This number strikes a balance between complexity and accuracy, more bases would allow more complexity but would also introduce a greater chance of errors, whereas fewer bases would provide greater accuracy while sacrificing complexity.
Cellular structures are vital to life on Earth – they are the most fundamental unit of complex organisms, and the smallest combination of materials that can be considered alive. They enable the partial isolation of materials and play host to chemical reactions. In doing so they enable homeostasis – a key feature of life whereby it maintains its thermodynamic disequilibrium with its surroundings.
These are the essential components that allow life on Earth to exist, grow, reproduce and influence their environment. In addition, they must be present, in some form or another, in any kind of life, be it alien or terrestrial.
We'll now move on to discuss how each of these foundations may realistically vary from their manifestations on Earth.

2.2 Alien Life: The Chemistry

Having discerned the four components at the basis of all life on Earth, we can begin to build an understanding of what forms life might take elsewhere in the Universe.[2]
Let's consider each building block in turn. Firstly, some basis of complex chemicals is needed for life to exist. As covered in Section 2.1, life on Earth is built from carbon-based chain-like molecules. Since a similar degree of chemical complexity would be needed for life to exist elsewhere, the question becomes: what alternatives are there to Carbon?
Any element that can form long molecular chains may be a viable alternative. The options are Boron, Nitrogen, Phosphorous, Sulfur and Silicon.
In ammonia, Boron can bond with Nitrogen and display analogous properties to the Carbon-Carbon bond. Such a basis can reproduce the chemistry of many hydrocarbons while boasting greater thermal stability. The issue is that life can only work with what it finds an abundance of, and Boron is a relatively uncommon element in the Universe (with a mass fraction of only 10 parts-per-million on Earth). Thus, a biological system relying on abundant Boron appears very unlikely.
Nitrogen is a very common element yet the N-N bond is too unstable to form long molecular chains on its own. This becomes possible when Nitrogen is combined with Boron, Carbon, Phosphorous and/or Sulfur, but this additional degree of complexity compared to the simple C-C bond likely precludes Nitrogen as a biological bedrock.
Sulfur and Phosphorous deliver a poor variety of chemicals which, in turn, can only exist within a narrow range of environmental conditions. Thus these elements are an incredibly unlikely basis for life.
Finally, Silicon is by far the best alternative to Carbon due to its chemical similarities. It can form four stable bonds creating myriad long molecular chains, opening up the possibility of a complex Silicon-based biochemistry. The difficulty with Silicon is that it can only form life-sustaining chemicals under the following conditions:

- Temperatures in excess of 220°C or below 0°C.
- A much higher pressure environment than on the surface of Earth.
- An absence of Oxygen (the second most common reactive element in the Universe).
- A non-water solvent (possibly methane or methanol).
- A relative absence of Carbon (the third most common reactive element in the Universe).

As such, after careful analysis, Carbon emerges as the only *realistic* chemical basis for life due to its ubiquity in the Universe, its complex chemistry, and the stable yet modifiable nature of Carbon-based macromolecules. In addition to a Carbon base, alien biochemistries are also likely to rely heavily on the CHON elements since they are the four most abundant reactive elements in the Universe *and* their complex molecular configurations have been found in many astrophysical bodies.

2.3 Alien Life: The Solvent

There are many compounds that have the capacity to exist in liquid form in a planetary environment, yet water appears special. Other candidates (such as various acids, Methane, Ammonia, and Nitrogen) all suffer from one or more of the following issues:

- Narrow temperature range for liquid state.
- Inability to dissolve biologically important molecules.

[2] The information provided in Sections 2.2 and 2.3 comes from *Life in the Universe: Expectations and Constraints* by Dirk Schulze-Makuch and Louis N. Irwin

- Low universal abundance.
- Low local abundance (only trace amounts on planetary bodies).
- Extremely low temperature needed for liquid state.

The final point is an important one as water can exist as a liquid at a higher temperature than any other solvent candidate. This allows for a high degree of free energy which could instigate the organisation of complex chemicals into life. Conversely, liquid Methane and liquid Nitrogen require very low temperatures and thus contain comparatively small amounts of free energy which could make the formation of life far more difficult or even impossible.
Only water has a broad temperature range (at high temperatures), and significant abundance in the universe. So thus far, Carbon-based life residing in a water solvent appears the only realistic manifestation of life in the Universe – i.e. the only form of life that doesn't require unusual abundances, tight restrictions, and incredibly stable environmental conditions.

2.4 Alien Life: Information Storage

The information storage system used on Earth is built from nucleic acids in a base-4 system. There is no reason to disallow alternative molecular mechanisms as DNA and RNA are not the only carbon-based chemicals capable of performing this function. They aren't even the only nucleic acids that could serve life in this way.[3]
However, as was explained in Section 2.1, the base-4 system utilised by life on Earth is optimal to balance accuracy and complexity. This holds no matter the chemical system at work as this enters into the realm of computation. For this reason, alien life may not use the same genetic information system as terrestrial life, but whatever system is used should behave in a very similar way, meaning the macroscopic properties of genetics (reproduction, inheritance, adaptation...) should remain the same.

2.5 Alien Life: Cellular Structures

Cell-like structures are fundamental to life on Earth and any life that satisfies the definition above would need cells to host the various processes that contribute to the maintenance of homeostasis and reproduction of the organism. As stated previously, cells are the smallest quantity of materials that classes as living. As such, these should be the first living entities to form anywhere that life exists, meaning that any complex alien life will develop from cells, just has terrestrial life has done.
Furthermore, the reliance of cells upon transport of chemicals through their boundaries creates another constraint on their size. The surface area of a cell must allow enough chemical flux at the boundary to sustain the volume contained within. Thus, the surface area to volume ratio of cells could have a universal range (microns to millimetres) meaning it is reasonable to expect alien life to be composed of small cell-like structures.

In conclusion, we would in fact expect alien life to be fundamentally very similar to life on Earth. It would be unrealistic for anything other than carbon-based, cellular life, utilising a water solvent and an organic information system to exist.
With that in mind, we can now move onto a discussion of planet habitability with a good idea of what properties a habitable planet must have.

[3] Morihiro et. al., *Biological applications of xeno nucleic acids*, Molecular Biosystems, Volume 13, Issue 2, Pages 235-245, (2017)

3 PLANET HABITABILITY

After developing a strong idea of what alien life might look like on its most fundamental level, it becomes possible to discuss planet habitability. Ultimately, we want to discern two things: what features must a planet have in order to be habitable, and how special these planets may be. This discussion will be limited to terrestrial (i.e. rocky) planets because gas giants would provide an unsuitably high-pressure environment.
In order to be habitable, a terrestrial planet must have the following properties[4]:

- It must host significant amounts of liquid water.
- It must be able to retain an atmosphere.
- Some means of stabilising the atmosphere against geological processes must be set up.

The plausibility of a planet satisfying each of these criteria will be discussed in detail. Additionally, the differing fates of Mars, Earth and Venus will be considered to ascertain how potentially habitable planets can become uninhabitable.

3.1 Liquid Water

Earth is often thought of as a water-rich planet, yet water constitutes only 0.02% of Earth's total mass.[5] Furthermore, almost all water on Earth exists on its surface which indicates our planet *became* wet some time after its formation. Understanding how the Earth acquired its water can help us to determine how likely it is that other such planets will do the same.
A crucial concept here is that of the *snow line*. When a star forms, it pulls in the gas and dust around it into the shape of a disc. As the star burns, it heats the disc. The closer any given point in the disc is to the star, the hotter that point will be. Close-in to the star, the high temperatures preclude water from condensing onto dust grains in the disc. However, as you move away from the star you eventually reach a point where water will freeze straight onto dust grains. See Figure 3 for a pictorial representation of the H_2O snow line in the Solar System.
Gas-giant planets get built up outside the snow line, meaning they once contained vast amounts of ice permeated through their rocky cores. Planets within the snow line (such as the Earth), however, form as dry, rocky places with no water to be found in any form.
So how does water trapped in comets and asteroids beyond the snow line make its way to Earth? The key lies in *planet migration*, a process by which planets can move in and out of position, dragging around water-rich objects in the process.
In the Grand Tack model,[6] Jupiter and Saturn underwent a swift inward migration before moving back outward to their current positions today. In doing so, they dragged along many water-rich objects and 'flung' them towards Mars, Earth and Venus. Since the water was largely trapped within the structures of these objects, it could not evaporate into the vacuum of space and the surfaces of these three planets became bombarded with the materials that would go on to form oceans.

[4] These properties and the discussion of biogeochemical cycles follows from information given in Chapters 5 and 16 of *Fundamental Planetary Science: Physics, Chemistry and Habitablity* by Jack J. Lissauer and Imke de Pater (2013)
[5] https://phys.org/news/2014-12-percent-earth.html
[6] See the article here for a more detailed description of Jupiter's Grand Tack: https://planetplanet.net/2013/08/02/the-grand-tack/

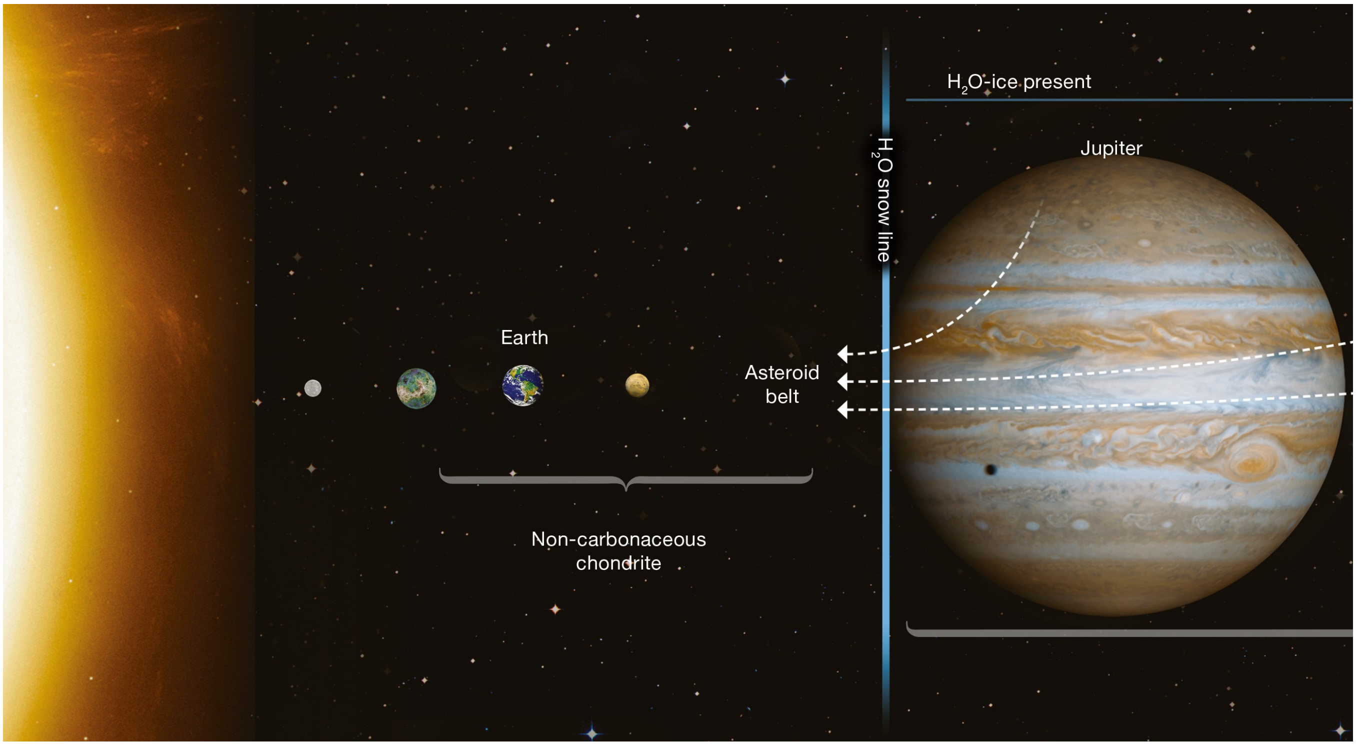

Figure 3. The snow line for water in the Solar System is shown. The Earth is visibly too close to the Sun to form from water-rich dust grains. The dotted lines indicate the dragging of icy comets past the snow line by Jupiter and Saturn during the Grand Tack. Reproduced from https://www.ritsumei.ac.jp/research/radiant/eng/space/story1.html/.

This shows that the presence of liquid water on a planet is not simply a matter of having the right surface temperature – although, this is still necessary once the water arrives. It is very possible that only planet migration is able to deliver water to terrestrial planets. Planet migration is a common phenomenon but it is believed to be very unpredictable, possibly generating results specific to each individual system in which it occurs. If the planet migration that occurred in our solar system is unique, then the likelihood of water oceans existing on terrestrial exoplanets may be very low.

3.2 Retaining an Atmosphere

Planets build their atmospheres early on when gas trapped within their rocky bodies leaks out to the surface. An atmosphere is essential to life as it provides the necessary pressure to prevent liquid water boiling off from the surface. Atmospheric gases are retained by the planet's gravitational pull but can gradually 'leak away' by gaining enough energy to escape. There are 5 dominant mechanisms by which this can occur[7]:

- Thermal Escape
- Chemical Escape
- Photochemical Escape
- Sputtering
- Impacts with meteorites

Thermal escape is where gas around a planet becomes heated to the point where it has enough energy to escape the planet's gravity.
Chemical escape occurs when energy transferred from chemical reactions ejects atoms or molecules from the atmosphere.
Photochemical escape affects molecules in the upper atmosphere as electrons energised by solar radiation split molecules and eject their atomic constituents into space.
Sputtering is when charged particles in powerful solar winds 'boil away' large parts of the outer atmosphere – a phenomenon the Earth defends itself against by deflecting these particles with its magnetic field.
Finally, **impacts with meteorites** can blast away parts of the atmosphere very effectively.
Impacts and sputtering have the greatest potential to cause significant atmospheric losses. To some extent, planets can replenish their atmospheres through volcanic activity, but it remains vital for habitability that a planet is not overly vulnerable to any of the above processes. This ability to retain *and defend* its atmosphere is a cornerstone of what makes the Earth habitable.

3.3 Stabilising the Atmosphere: Biogeochemical Cycles

As mentioned above, planets release gases trapped beneath their surface to build their atmospheres. This continues long into the lifetimes of these planets, meaning that greenhouse gases such as CO_2 and Methane are continually released into the atmosphere. Such geophysical processes increase the planet's greenhouse effect, causing greater heating which, on a world with water oceans, can cause runaway heating. This process will be described when the history of Venus is covered in Section 3.4.

[7] See this article for the ways planets can lose their atmospheres. This also informed the discussion of Mars in Section 3.4: https://www.scientificamerican.com/article/how-planets-lose-their-atmospheres/

Furthermore, the albedo of a planet (a measure of its reflectivity) can also cause runaway effects. If the planet cools then water turns to ice on the surface. This increases the planet's reflectivity, making it harder for the planet to retain energy from the Sun's radiation. This cools the planet further, creates more ice, and further increases the planet's albedo. The cycle of positive feedback continues and can result in a completely ice-covered planet. This in fact occurred on Earth about 700 million years ago (mya) – an event that is referred to as the *snowball Earth*.

These positive feedback cycles create instability. Thus, habitable planets require some way of regulating their greenhouse effect, thereby maintaining a moderate temperature.

On Earth, this comes in the form of the *carbonate-silicate cycle* (shown in Figure 4). Carbon dioxide in the atmosphere reacts with water and silicates in the Earth's crust in a process called weathering. Rivers deliver these reaction products to the oceans where they are locked into sediments – living organisms accelerate this process by building shells out of Calcium Carbonate ($CaCO_3$). Tectonic activity drags the carbonates deep into the mantle where it reacts with Silicon Dioxide (SiO_2) to form $CaSiO_3$ (a mineral called *Wallastonite*) and producing CO_2 beneath the Earth's surface. This CO_2 is then released back into the atmosphere by volcanic activity.

The crucial point here is that this acts as a *negative* feedback cycle. Weathering rates are strongly temperature-dependent – if the planet warms then weathering rates increase, removing more CO_2 from the atmosphere and allowing the planet to cool through a reduced greenhouse effect. Conversely, if the planet cools then weathering rates decrease and the greater concentration of CO_2 in the atmosphere counteracts this cooling.

This cycle has maintained moderate temperatures on Earth for billions of years and is a necessary component of its habitability. Without tectonic and volcanic activity, the Earth could not replenish its atmospheric CO_2 – potentially leading to a snowball Earth. Additionally, without enough water, the carbonate-silicate cycle could not extract enough CO_2, potentially leading to a runaway greenhouse effect. It becomes clear that there is a some degree of fine-tuning required to make a planet habitable *and* stable. To explore this further, let's take a look at Mars and Venus.

3.4 The Fates of Earth, Mars and Venus

It is known that Mars, Venus and Earth all had large quantities of water on their surfaces at some point in time. Yet only Earth is habitable, understanding why the fates of these three planets diverged can provide insights into how special Earth may be.

Mars and Earth were once very similar – wet worlds with strong magnetic fields and CO_2-rich atmospheres. Yet today Mars has no atmosphere and little-to-no surface water. The key difference between the two worlds is their size – Mars is about half the size of the Earth.[8]

Mars' small stature meant it was able to cool quickly after it was formed. As a result, the convective currents in its metallic core slowed to a stop, killing the magnetic field and halting volcanic activity. This left Mars' atmosphere vulnerable to solar winds which, through sputtering, stripped about 90% of it. The absence of volcanic activity made matters worse as Mars had no way to replenish the atmosphere it was rapidly losing. This likely indicates some sort of minimum size requirement for a planet with stable habitability.

[8] https://science.nasa.gov/mars/facts/

Venus and Earth are very similar in size yet the former has become the hottest planet in the Solar System with a dense CO_2-rich atmosphere and almost no water. This difference arose when Venus became the victim of a runaway greenhouse effect.[9] This was caused by an inefficient Carbon Cycle on Venus, likely due to insufficient water-content on the planet's surface (perhaps because of its close proximity to the Sun). As its oceans began to evaporate, its CO_2-rich atmosphere became augmented with gaseous water. This increased the greenhouse effect, which increased heating, which evaporated more of the oceans, thereby creating the runaway greenhouse effect. Thus, it would appear that there may be some minimum to the water content of a planet with stable habitability.

The Earth is stable in its habitability for the following reasons:

- Tectonic and volcanic activity replenish atmospheric CO_2, counteracting runaway cooling.
- Sufficient surface water absorbs atmospheric CO_2, preventing runaway heating.
- It is large enough to have retained the magnetic field created by its molten core, thereby defending its atmosphere.
- Its position in the Solar System allows it to host liquid water.

In addition to the delivery of water from beyond the snow line, these constraints must be imposed on any habitable planet. Another noteworthy feature of the Earth is that it is the only planet in the solar system that experiences tectonic activity. This could introduce yet another reason to believe the Earth is a very special planet.

If habitable planets must satisfy such specific criteria, it drastically limits the number of life-hosting planets we expect to exist in our galaxy.

4 FORMING LIFE

It is known from geological studies of meteorites that the solar system was being formed about 4.6 billion years ago, meaning the Earth is of similar age. However at this time our planet was an uninhabitable clump of molten rock. As the earth cooled, it had water delivered to it from asteroids and comets in a process which finished at the end of the 'Late Heavy Bombardment about' 3.9 billion years ago.[10]

The earliest signs of life on Earth date back 3.7 billion years, meaning *biogenesis* (the formation of life from non-living materials) occurred within a few hundred million years of the Earth becoming a suitable host for life. This is often taken to mean that life will form readily when the environmental conditions allow it. This is certainly not an outrageous conclusion to come to, but it is inevitably accompanied by a high degree of uncertainty since this extrapolates a statistical pattern from a sample of one.

It is true that Earth is more likely to be representative of a typical biogenesis timescale than a large deviation from it, yet this cannot be ruled out entirely, meaning biogenesis could still be an exceedingly rare event even though it happened quickly on Earth.

Additionally, there is the possibility that life that forms quickly is then able to regulate its environment to maintain the planet's habitability. This could have been the case on Earth as life accelerated the carbonate-silicate cycle, perhaps preventing a runaway greenhouse. If the survival of life requires early formation, to prevent runaway

[9] https://www.esa.int/Science_Exploration/Space_Science/How_Venus_and_Mars_can_teach_us_about_Earth

[10] https://www.space.com/36661-late-heavy-bombardment.html

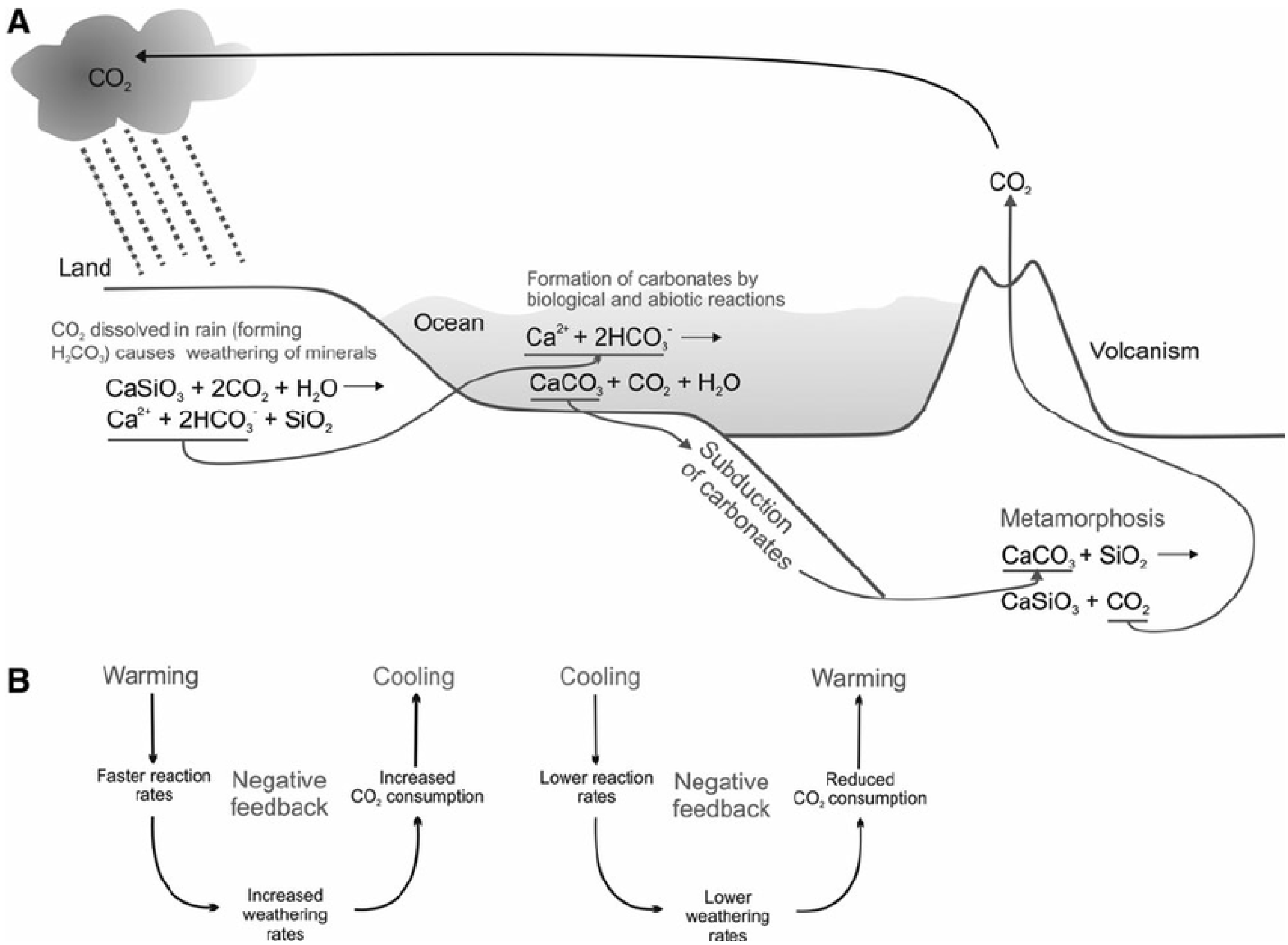

Figure 4. The carbonate-silicate cycle is shown in panel A alongside the chemical reactions that entrap Carbon in sediments before it is transferred to the mantle and released by volcanism. The negative feedback cycle that maintains Earth's moderate temperatures on billion-year timescales is shown in panel B. Reproduced from Cockel et. al. *Habitability: A Review*, Astrobiology, Volume 16, Number 1, Pages 89-117, (2016).

heating or for any other reason, this would completely invalidate any statistical conclusions from biogenesis on Earth.

To illustrate this, imagine we could build a sample of perfectly stable habitable planets and wait for biogenesis to occur on each of them. The times at which biogenesis occurs would follow a bell-curve (as shown in the top panel of Figure 5). When this statistical pattern is exposed to the necessity of early formation, the only examples of life that remain are those that formed early in their planet's history. Not because this is simply what happens under the right conditions, but because this is what must happen to ensure survival. This would make any statistical conclusions drawn from the Earth's history completely meaningless.

From what we know about the Earth's history, there is no reason to believe this is a requirement of life everywhere, but it does serve to highlight the dangers of drawing statistical conclusions from a sample of one.

The real conclusion to be drawn here is that it is nearly impossible to argue either way whether biogenesis is common or rare, fast or slow, because there is simply a lack of data. If life were to be discovered elsewhere in the galaxy then estimates could start to take on more meaning.

5 SINGLE CELLS TO COMPLEX LIFE

Say that life has emerged on a stable, habitable planet. It now embarks on the next stage of the journey to producing a technologically advanced civilisation – evolution. This involves the development of crude single-celled organisms first into multicellular systems, and then into complex creatures with specialised groups of cells divided into organs and tissues (this kind of lifeform is called a *metazoan*). By studying how this happened on Earth, a lot can be learned about how life becomes more complex and what it needs to do so.[11]

5.1 Life on Earth

As mentioned in Section 4, biogenesis appears to have occurred on Earth at least 3.7 bya. Life at this stage was utterly simple and it took another billion years before cells developed specialised parts like a nucleus for storing DNA. There is evidence for multicellular life existing in simple macroscopic structures 2 billion years after this

[11] Section 5.1 is informed by https://naturalhistory.si.edu/education/teaching-resources/life-science/early-life-earth-animal-origins

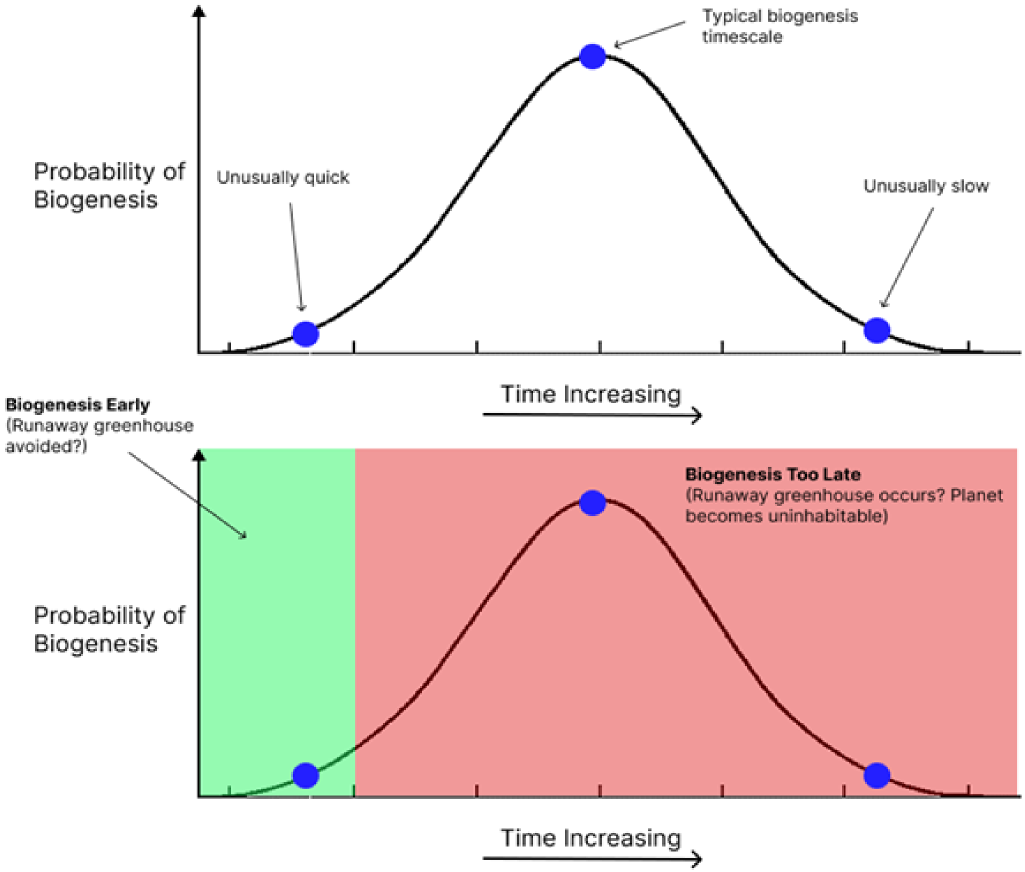

Figure 5. The bell curve that shows the typical or unusual timescales for biogenesis is shown in the top panel. The Earth is more likely to appear near the peak of the curve rather than at either tail. The bottom panel shows the effect of mandatory early biogensis on the statistical sample. The sample is filtered to only include examples of early biogenesis.

point. But up until around 540 mya, life was very simple. Then there came a very rapid development (within roughly 60 million years) of lifeforms with features like heads, tails, brains and other organs in a period of time termed the *Cambrian Explosion*. This set the stage for modern life with a steadier degree of development up to the present day. Figure 6 presents a timeline of the evolutionary history of life on Earth.

5.2 The Cambrian Explosion

Life existed for 1 to 2 billion years before multicellular life formed. Additionally, life had existed for over 3 billion years before the basic features of complex life burst into existence. The swift nature of this development may indicate that there was a great deal of evolutionary potential that was being somehow 'bottled-up'. Understanding the possible causes of the Cambrian Explosion (or lack thereof – perhaps it was a moment of pure chance) can provide clues as to how evolution may occur on other planets.[12]

It is believed that the Cambrian Explosion was triggered by environmental factors, such as changes in seawater composition, increases in nutrient availability, and oxygenation of the atmosphere, with the latter appearing to be the best candidate. Ecological causes such as predator-prey pressure driving innovative new attacking/defensive mechanisms have been proposed, but these appear to be accelerating forces rather than triggers (predation appears to have come into existence after the beginning of the Cambrian Explosion). Thus, it appears probable that environmental triggers created space for ecological drivers which fueled the rapidity of the event.

As with most parts of this essay, the question becomes: was an event like this inevitable, so unlikely that it won't happen anywhere else, or somewhere between the two?

Let's return to this idea of atmospheric oxygenation. Rising oxygen levels drive evolution in two primary ways. Firstly, the intake of Oxygen results in the accumulation of reaction products toxic to all organisms. This threat forces the development of defense mechanisms and workarounds – it is in fact believed that this could have driven the development of single-celled life into multicellular organisms. Secondly, metazoans – a much more mobile form of life compared to plant life – require oxygen for many aerobically expensive physiological processes (meaning they use oxygen inefficiently). Hence, an increase in oxygen availability would increase the capacity for these organisms to thrive.

There is strong evidence for tectonic activity and deglaciation of the Earth giving rise to significant oxygenation of the atmosphere. The implication being that oxygen levels have played a crucial role in the

[12] This section uses information provided in Zhang et. al., *Triggers for the Cambrian explosion: Hypotheses and problems*, Gondwana Research, Volume 25, Issue 3, Pages 896-909, (2014)

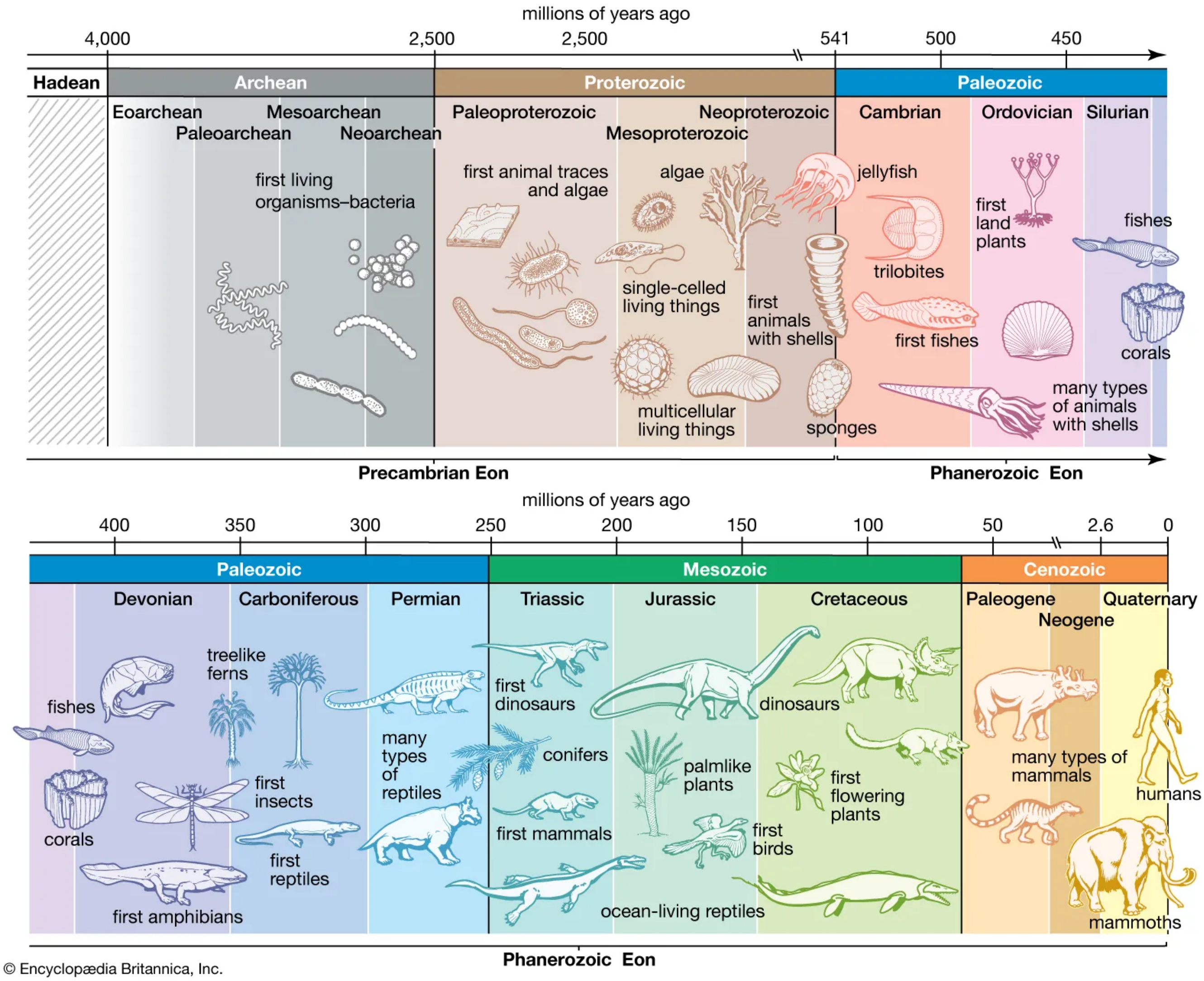

Figure 6. The evolutionary history of life on Earth. Pre-Cambrian life was very simple before giving way to more complex organisms from 541 mya. Reproduced from https://www.britannica.com/science/Cambrian-explosion.

evolution of life on Earth.
So now the question transforms again – is oxygen crucial for *all* complex life, or just for life on Earth?

5.3 The Uniqueness of Oxygen

It has been argued[13] that molecular Oxygen gas (O_2) is indeed a prerequisite for complex life due to its unique properties. It releases more energy per reduction reaction (the gaining of an electron) than any other element, except Fluorine and Chlorine. However, unlike Fluorine and Chlorine, Oxygen forms a very stable gas allowing stores of O_2 to be built up in an atmosphere over time.
Altogether, this makes O_2 gas a life-sustaining energy source with no equal. As such, a planet's "oxygenation time" (i.e. the time it takes to build an oxygen content capable of sustaining complex life) becomes an important factor in its habitability. On Earth, it took nearly 4 billion years to reach this threshold – 40% of the Sun's total lifetime. This alone could preclude stars, say, more than twice the size of the Sun from hosting planets with complex life (due to their shorter lifetimes).
It is difficult to know whether the Earth's oxygenation was quick or slow, typical or unique. But this does demonstrate that much looser restrictions exist for simple life than for complex life – ensuring that the development of the former into the latter is far from a trivial matter.

[13] In Catling et. al., *Why O2 is required by complex life on habitable planets and the concept of planetary "oxygenation time"*. Astrobiology, Volume 5, Number 3, Pages 415-438, (2005)

6 INTELLIGENCE & TECHNOLOGY

Once complex life has begun to emerge, does the development of intelligence follow easily? And how likely is an intelligent species to develop technology? These are the last stages of development, after

which a technological civilisation emerges. Once again, analyses of life on Earth can inform our expectations of extra-terrestrial life.

6.1 Animal Intelligence

On Earth, many animal species display some degree of intelligence[14] be it in the form of communication, collaboration, use of tools or problem solving. Examples include:

- Cephalopods (squid, cuttlefish, octopus...)
- Primates (apes, humans...)
- Cetaceans (dolphins, whales...)
- Social insects (ants, bees...)
- Corvids (crows, ravens, jays...)

Of particular note is the octopus. Octopuses are the closest thing to alien intelligence that exists on Earth. This is because their evolutionary path diverged from humans around 550 mya, even before the first dinosaurs (see Figure 7).[15] In addition, their intelligence is very different to our own. While our neurons are concentrated in our heads, theirs are spread throughout their body, allowing them to control the colour and texture of their skin within seconds.

Despite the differences, they also display similar intellectual abilities to primates and humans, such as problem-solving, use of tools, facial recognition, and capacity for play.[16]

Octopuses represent an example of *convergent evolution* of intelligence – a phenomenon responsible for similar features like the eye cropping up in unrelated evolutionary branches.

Such a plethora of examples of intelligence among life on Earth indicates that the competitive advantage offered by greater intellect drives its evolution. It should be expected then, that if complex life were to arise on a different planet, then ecological incentives should power the development of intelligence.

However, humans are the only example on Earth of the kind of intelligence required to produce sophisticated technology and civilisation. So a discussion of how this arose is required.[17]

6.2 Human Intelligence & Civilisation

Humans began to diverge from the great apes about 6 mya. The earliest evidence of human ingenuity dates back to 2 mya in the form of primitive stone tools believed to be relics of *Homo Habilis*. Advances in cranial capacity and technological sophistication continued until modern humans developed about 150,000 years ago. Fledgling forms of art, politics, religion, science and syntactic language appeared 60,000 to 30,000 years ago. From there, hunter-gathering slowly gave way to agriculture and civilisation, with the first seeds of modern civilisation taking shape 5,000 years ago.

Human-level intelligence has obvious advantages over that of animals. It has allowed us to build shelter, invent weapons, communicate like no other species and influence our environment to the extent that the only real threat to our species is our own progress.

Our brains evolved from those of great apes and the foundations of our intelligence (symbolic cognition, creativity and problem solving) have been observed in these animals today. This suggests that, while human intelligence is comparatively advanced, it is not special. Our brains are large and incredibly well connected[18] but the building blocks of our intellect are not unique to us.

This indicates that human intelligence is simply an extension of evolutionary pathways millions of years in the making. In this sense, human-level intelligence appears to be something that could arise among complex lifeforms if given enough time. Additionally, the fact that modern humans existed for about 150,000 years before reaching technological civilisation (compare this to the 50-million-year Cambrian Explosion) means that once the intellectual capacity has developed, civilisation can occur relatively quickly. Thus, the development of intelligence and civilisation from complex lifeforms does not appear to be a bottleneck in the process.

6.3 A Final Note on Oxygen

It has been argued[19] that the threshold oxygen content needed for complex life (as discussed in Section 5.3) is actually much lower than the threshold for technological civilisation. This is due to the importance of fire in the development of advanced technologies. Open-air combustion (which relies on an abundance of Oxygen) has been crucial to humans for cooking, crafting materials for tools and shelters, and extracting the energy stored in fossil fuels.

It also appears that this was only possible once the Oxygen content of Earth's atmosphere exceeded 18%. Thus, even *if* a planet with low oxygen levels could develop complex life, the absence of a craftable and controllable source of energy could prevent the development of any advanced technological civilisation. Furthermore, a planet with enough Oxygen to sustain complex life may not possess enough to produce a technological civilisation.

This adds one more degree of planetary fine-tuning to the prerequisites for the existence of alien technological civilisations.

7 CONCLUSION

After everything that has been covered in this essay, we can say with confidence that for an alien technological civilisation to exist:

(i) A planet must form that is sizeable enough to retain its atmosphere and magnetic field.
(ii) It must form at an appropriate distance from its star to host liquid water.
(iii) Migration in the planetary system must deliver water to the planet.
(iv) Tectonic and volcanic activity must combine with sufficient water content to set up global temperature regulation.
(v) Biogenesis must occur on that planet.
(vi) Oxygenation must occur on a timescale significantly shorter than the lifetime of the host star.
(vii) Evolution must continue until a highly intelligent species develops.
(viii) That species must develop a technological civilisation.

[14] https://www.scientificamerican.com/article/intelligence-evolved/
[15] Schnell et. al., *How intelligent is a cephalopod? Lessons from comparative cognition*, Biological Reviews, Volume 96, Issue 1, Pages 162-178, (2020)
[16] https://www.scientificamerican.com/article/the-mind-of-an-octopus/
[17] Section 6.2 uses information from *The Evolution of Human Intelligence* by L. Gabora,, and A. Russon, published in Chapter 17 of *The Cambridge Handbook of Intelligence* edited by R. Sternberg and S. Kaufman
[18] See again this article: https://www.scientificamerican.com/article/intelligence-evolved/
[19] See this article: https://www.rochester.edu/newscenter/atmospheric-oxygen-cosmic-technospheres-alien-technology-589242/

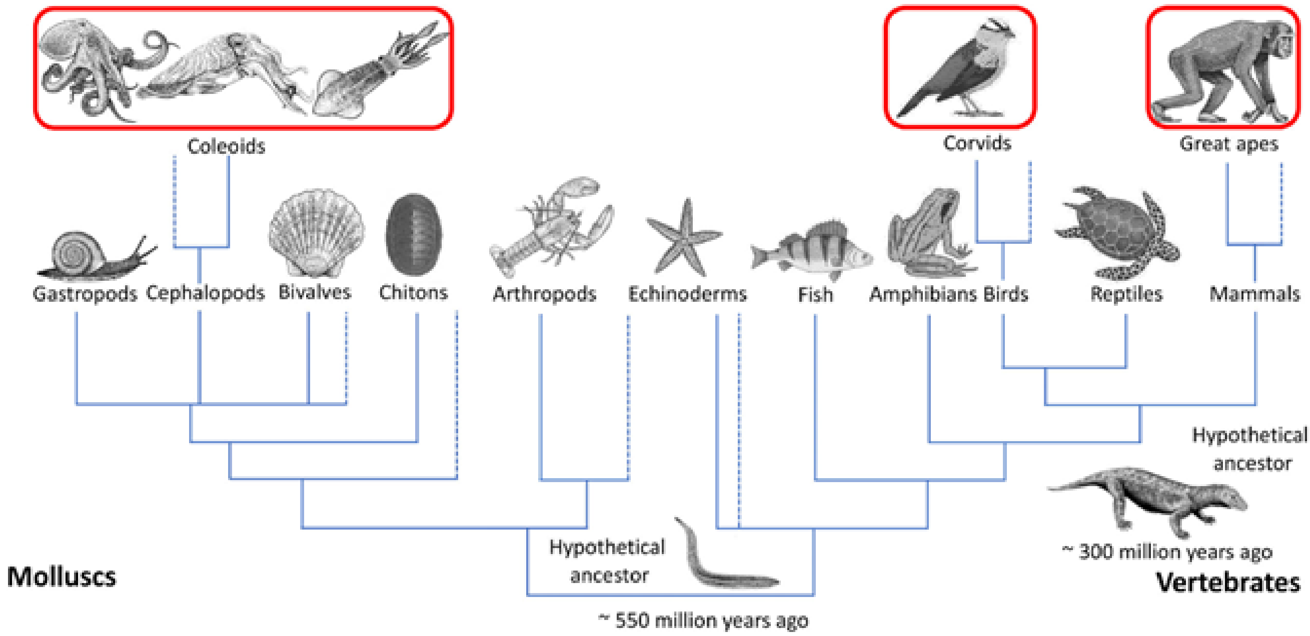

Figure 7. The last common ancestor of octopuses and humans is shown. The evolutionary branches split before any intelligent animals were in existence. Reproduced from Schnell et. al. (2020) – see footnotes.

As has been discussed, there are numerous bottlenecks in this process – most importantly the formation of a stable, habitable planet, and the oxygenation that allows complex life to develop. Additionally, the host star must have a long enough lifetime to support evolutionary timescales on the order of billions of years. This limits the number of stars in the Milky Way that could host planets with alien civilisations. Although, it should be noted that the majority of stars in our galaxy would have sufficient lifetimes to satisfy this criterion.

With so many unknowns (e.g. the likelihood of biogenesis) it is impossible to construct any meaningful estimate of how many alien civilisations may be present in our galaxy. But the opinion of the writer is that the degree of fine-tuning required to produce a habitable planet, in conjunction with the oxygenation constraint make technological civilisations exceedingly rare. As such, it would appear that the existence of alien civilisations in our own galaxy is a very unlikely prospect.

The only civilisations we could conceivably communicate with are those that share our galaxy with us. The Universe as a whole is so infinitely large that the suggestion that we are the only intelligent civilisation to exist *anywhere* is ludicrous. For that reason it would appear we are alone, but we're not the only ones.